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AN AIRSPACE DESIGN SYSTEM USING A GRAPHICS WORKSTATION - THE PILOT PROJECT

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by

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Transport Canada / Transports Canada

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LANGUAGE NOTICE

Un sommaire en français de ce rapport est inclus avant la Table des matières.

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16. Abstract

This report presents the results of the pilot implementation of an Airspace Design System on a high-performance 3D graphics workstation.

The purpose of this pilot project was to demonstrate the feasibility of computer aided design and evaluation of flight procedures.

The design of flight procedures, including airways and instrument approaches involves the identification of critical airspace around the ideal flight path of an airway and the evaluation of the critical airspace with reference to safety criteria.

A pilot system was developed as an integrated software tool implemented on a Silicon Graphics Workstation. A flight procedure design specialist can use the pilot system to design, validate and evaluate ILS instrument approach procedures.

It is shown that a user-oriented man-machine interface approach and the capturing of expert knowledge in flight procedure design can team up with the visualization and computation capacity of the new generation of high-speed 3D graphics workstations to provide a complete environment for flight procedure development.

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16. Resume

Ce rapport traite des résultats de l'exploitation pilote d'un Système d'aménagement de l'espace aérien fonctionnant sur poste d'infographie tridimensionnelle à haute performance.

Le but de ce projet pilote était de démontrer qu'il était possible de concevoir et d'évaluer des procédures de vol à l'aide d'un ordinateur.

La conception des procédures de vol, qui inclut la définition des voies aériennes et des approches aux instruments, comprend l'identification de l'espace aérien critique autour de la trajectoire de vol idéale dans une voie aérienne et l'évaluation de cet espace aérien par rapport aux critères des sécurité.

Un système pilote a été conçu sous forme de logiciel intégré fonctionnant sur un poste d'infographie Silicon Graphics. Un spécialiste en conception de procédures de vol peut utiliser le système pilote pour concevoir, valider et évaluer des procédures d'approche au instruments (ILS).

Il a été démontré qu'il est possible de jumeler une interface homme-machine spécialement conçue pour l'utilisateur et les connaisances techniques d'un expert en conception de procédures de vol aux capacités de visualisation et de calcul des postes d'inforgraphie tridimensionnelle à haute performance de nouvelle génération afin d'obtenir un environnement informatique complet pour l'élaboration des procédures de vol.

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SUMMARY

Introduction

Aircraft operating under Instrument Flight Rules (IFR) fly on predetermined flight paths from take-off to landing. To ensure safe operation of aircraft in flight, these paths must be designed based on established criteria. The flight procedure design criteria specify the method, allowable tolerances, units of measurement and accuracies for the various phases of an aircraft's itinerary.

Transport Canada's Aeronautical Information Services (AIS) with the financial support of the Transportation Development Centre initiated a pilot project to build a computer aided design system for the design of airways and instrument approach procedures. This report presents the results of the pilot implementation of the Airspace Design System (ADS) by Virtual Prototypes Inc. and suggests recommendations for future development of the system.

The conceptual ADS is an integrated software tool implemented on a high-performance 3D graphics workstation. The pilot ADS implementation set out to prove the feasibility of the ADS concept and to initiate the development process of the full-scale system.

The scope of the pilot system was restricted to a specific test region covering the southern parts of Ontario and Quebec. A design module for computing an Instrument Landing System (ILS) instrument approach procedure was chosen as a test module for implemention in the pilot project.

The major system components of ADS are the flight procedure design expert system, the man-machine interface (MMI), the graphics manager and the data manager. The main efforts in the pilot system development were:

- to provide a flight procedure design domain environment that replaces and improves on that of the existing manual process;
- to design a flexible and easy to use MMI;
- to develop a terrain model based on digital terrain elevation data (DTED);
- to establish a centralized on-line data base of the navigational facilities and obstructions;
- to build a prototype flight procedure design expert system and
- to provide other support tools and utilities.

Results

This pilot project took 18 months and involved up to four software engineers working in parallel at the coding phase. Approximately 40% of the effort was expended on studying the problem domain and the user requirements, and on preparing an in-depth conceptual design of the perceived full-scale system. The pilot project has succeeded in meeting the requirements initially set out, and in providing the direction for future development.

The pilot system was implemented on a Silicon Graphics Iris 3130 workstation. This workstation was subsequently installed at the Ottawa office of AIS for user evaluation of the pilot system.

The pilot system provides the flight procedure designer with a complete design domain environment that centralizes design domain information; is easy to use; and offers three-dimensional visualization.

DTED are used for generating the graphic displays of the design domain. They are also used in flight domain computations. The pilot implementation verified the validity of using DTED to replace paper topographical charts. The 3D perspective terrain modeling based on DTED provides a completely new visual dimension.

An on-line data base of navigational facilities and obstructions in the test region was established for testing the operation of the pilot system. Substantial work, however, remains to be done in this area.

The approach used in the development of a computer aided flight procedure design tool was an expert system approach. A prototype expert system for designing ILS instrument approach procedures was constructed. The prototype expert system proved the viability of this approach. Future extension to the ADS expert system will involve careful knowledge engineering, extension of the scope of the knowledge base, and the provision of a better knowledge base development environment.

The pilot ADS has an array of useful tools and utilities to complement the major system functions. These features include an animated flythrough interface, an Instrument Approach Procedure (IAP) chart generation capability, a geodesic calculator tool and a desk calculator tool. The animated flythrough, with 3D perspective terrain modeling, simulates flight along the ideal flight path designed for an approach procedure. The IAP chart generation provides a graphic summary of the ILS instrument approach procedure designed with the ADS expert system. The other tools generally facilitate the flight procedure designer in his tasks.

Conclusion

The pilot system has touched the threshold that opens to a whole array of possibilities in using 3D graphics and knowledge engineering to assist in airspace designs and other related areas. Development of these possibilities is recommended.

Better hardware capability in the future would make it possible to improve both the graphics and the inference performance of ADS. In the area of knowledge engineering, it is important to involve the participation of human domain experts in addition to the use of written flight procedure design criteria documents. An improved interactive knowledge base development environment would augment the capability of ADS from a flight procedure design tool into a flight procedure criteria development environment.

The integration of a collision risk model into ADS for the evaluation of flight procedure design would also add to the capability of this powerful design tool.

Feedback generated by users of the pilot system would provide valuable information for the enhancement of the MMI component of the Airspace Design System.

SOMMAIRE

Introduction

Les aéronefs pilotés selon les règles de vol aux instruments (IFR) suivent un itinéraire prédéterminé entre le point de décollage et le point d'atterrissage. Afin d'assurer la sécurité des aéronefs en vol, ces itinéraires doivent être tracés selon des critères précis. Les critères de définition des procédures de vol établissent, pour les différentes étapes d'un vol, la méthode à suivre, les tolérances admissibles, les unités de mesure utilisées et les précisions à atteindre.

Les Services d'information aéronautique (AIS) de Transports Canada ont lancé avec le soutien financier du Centre de développement des transports un projet pilote visant l'élaboration d'un système de conception assistée par ordinateur qui servirait à la définition des voies aériennes à suivre et des procédures d'approche aux instruments à adopter. Ce rapport traite des résultats de la mise en oeuvre expérimentale du Système d'aménagement de l'espace aérien (ADS) par la compagnie Virtual Prototypes Inc. et contient des recommandations pour le perfectionnement du système.

Le système ADS est un logiciel intégré qui fonctionne sur poste d'infographie tridimensionnelle à haute perfomance. L'expérimentation du système ADS a été lancée afin de déterminer la faisabilité du concept et d'amorcer le processus d'élaboration d'un système complet.

La portée du système pilote a été limitée à une région précise couvrant le sud de l'Ontario et du Québec. Un module de conception servant à définir les procédures d'approche aux instruments dans un environnement ILS (système d'atterrissage aux instruments) a été choisi comme module d'essai pour la mise en oeuvre du projet pilote.

Les composants majeurs du système ADS sont: le système expert de définition des procédures de vol, l'interface homme-machine, le logiciel de gestion infographique et celui de gestion des données. Les principaux objectifs visés dans le cadre du projet pilote étaient:

- de fournir une représentation infographique de la zone visée par les procédures de vol (ci-après désignée zone-cible) afin de remplacer et d'améliorer le procédé manuel de conception existant;
- de concevoir une interface homme-machine flexible et facile à utiliser;
- d'élaborer une maquette informatisée de la zone-cible basée sur les données fournies par un numériseur de cartographie topographique (DTED);
- de constituer une base de données centralisée sur les aides à la navigation et les obstacles;
- de créer un prototype de système expert pour la définition des procédures de vol;
- de fournir d'autres outils de soutien et programmes utilitaires.

Résultats

Ce projet pilote d'une durée de 18 mois a exigé la collaboration de quatre ingénieurs en logiciels qui ont travaillé de pair à l'étape de programmation. Environ 40 p. cent des travaux ont été consacrés à l'étude de la zone d'essai et des besoins des utilisateurs, ainsi qu'à l'étude conceptuelle approfondie du système complet envisagé. Le projet pilote a permis d'atteindre les objectifs visés et de dégager l'orientation à donner aux travaux de perfectionnement du système.

Le système pilote a été mis en application sur un poste d'infographie Iris 3130 de la compagnie Silicon Graphics. Ce poste a ensuite été installé dans les bureaux des Services d'information aéronautique à Ottawa afin que les utilisateurs puissent évaluer le système pilote.

Ce système fournit au concepteur de procédures de vol une représentation infographique complète de la zone-cible et centralise toutes les données descriptives concernant cette zone; il est facile à utiliser et offre une visualisation tridimensionnelle.

Les données DTED servent à produire les affichages infographiques de la zone-cible. Elles sont aussi utilisées pour les calculs du domaine de vol. La mise en oeuvre expérimentale du système a permis de vérifier que les données DTED pouvaient remplacer les cartes topographiques. La modélisation tridimensionnelle de la zone survolée basée sur les données DTED offre une toute nouvelle dimension visuelle.

Une base de données sur les aides à la navigation et les obstacles de la région étudiée a été établie afin d'évaluer le fonctionnement du système pilote. Il reste cependant encore beaucoup de travail à effectuer dans ce secteur.

L'approche qui a été retenue pour l'élaboration d'un outil de conception de procédures de vol, assistée par ordinateur, est celle de l'utilisation d'un système expert. Le prototype de système expert de conception des procédures d'approche aux insturments (ILS) conçu, a permis de confirmer la viabilité de l'approche choisie. L'extension éventuelle du système expert nécessitera une application minutieuse de l'ingénierie de la connaissance, un élargissement de la base de connaissances et la création d'un système perfectionné de développement de cette base.

Le système pilote ADS comprend plusieurs outils et programmes utilitaires qui complètent les fonctions du système principal, soit un programme d'animation interactif, une fonction servant à créer des cartes d'approche aux instruments (IAP), un outil de calcul géodésique et une calculatrice. Le programme d'animation, grâce à la modélisation tridimensionnelle de la région survolée, permet de simuler un vol le long de la trajectoire de vol idéale d'une procédure d'approche donnée. La fonction IAP fournit une représentation graphique de la procédure d'approche aux instruments (ILS) élaborée par le système expert ADS. Les autres outils servent à faciliter le travail du concepteur de procédures de vol.

Conclusion

La mise en application du système pilote a permis d'entrevoir les nombreuses possibilités que peuvent offrir les représentations graphiques tridimensionnelles et l'ingénierie de la connaissance pour l'aménagement de l'espace aérien ainsi que dans d'autres domaines. Il est recommandé de développer ces possibilités.

Un matériel informatique plus performant devrait permettre d'améliorer la qualité de la visualisation infographique et les performances inférencielles du système ADS. En ce qui a trait à l'ingénierie de la connaissance, en plus d'exploiter les documents sur les critères de définition des procédures de vol. Il est important de faire appel à des experts dans le domaine. Une fonction améliorée du développement de la base de connaissances augmenterait les possibilités du système ADS et ferait de l'outil de conception de procédures de vol existant, un outil de conception d'élaboration des critères de procédures de vol.

L'ajout d'une fonction de calcul des risques d'abordage qui servirait à l'analyse critique des procédures de vol définies à l'aide de l'ordinateur augmenterait aussi les possibilités de ce puissant outil de conception.

La consultation des utilisateurs du système pilote permettrait de dégager des renseignements précieux dans l'optique d'éventuels travaux de perfectionnement de l'interface homme-machine du système d'aménagement de l'espace aérien.

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1. INTRODUCTION

1.1 Background

Aircraft operating under Instrument Flight Rules (IFR) fly on predetermined flight paths from take-off to landing. To ensure safe operation of aircraft in flight, these paths must be designed based on established criteria. The flight procedure design criteria [1][1] specify the method, allowable tolerances, units of measurement and accuracies for the various phases of an aircraft's itinerary. The flight procedure design criteria are used to design the ideal flight path of a flight procedure. Each ideal flight path is governed by its relationship to an Obstacle Clearance Surface (OCS). The safe operation along the flight path depends on obstacles, both terrain and man-made, not penetrating the OCS.

The flight procedure design criteria set down rules and limits based on the operating performance of the aircraft and the availability and accuracy of the navigation aids. The criteria are standards for guiding the flight procedure design specialists to design specific flight paths. Often the standards must be interpreted using the judgement of specialists to resolve specific problems. The present design criteria reflect the cumulation of knowledge and the evolution of methods used by design specialists in the past.

Until now, design specialists have prepared flight procedures manually, using topographical charts of various scales, templates, aerodrome site plans and other aeronautical information publications. The information needed by the specialists is often scattered and duplicated. The validity of the information is time-dependent. This leads to unavoidable redundancy and inconsistency. The need for lengthy calculation and detail drafting, checking and cross-checking makes it very difficult for the specialists to make minor adjustments or to try out alternative solutions.

With improved aircraft flight management – navigation systems and the introduction of new terrestrial and orbital navigation facilities, the criteria for designing safer flight paths must be revised. As new airports and better navigation facilities are added, existing flight paths must be re-evaluated and new ones must be designed. The current method of updating instrument approaches and airways will not be cost-effective as demands increase in the future.

Modification to existing criteria must be done carefully. The existing criteria account for past experience. Modification usually involves new and untested concepts. It is important that these new concepts be tried and tested and the possible alternatives evaluated before setting down the new directives.

New technological advancements in the area of computers suggest that the current situation can be greatly improved.

1 Numbers in brackets designate reference numbers in the list of references.

1. Government agencies in Canada and the United States have been working towards providing wide coverage of digital terrain data. This form of terrain data can be used directly by computers both for information search and for graphic displays. The use of such data in a computer system can replace the need for paper topographical maps.

2. Improved data storage and data management techniques on computers mean that information can be better organized and be made more accessible.

3. Knowledge representation and knowledge utilization by computers have been applied successfully to help laymen solve complex problems.

4. Powerful high speed graphics workstations have become a feasible hardware solution. It is important to take advantage of the high quality graphic visualization techniques of data and processes in providing a computer aided design environment.

Transport Canada's Aeronautical Information Services (AIS), with the financial support of the Transportation Development Centre (TDC), initiated a pilot project to build a computer aided design system for the design of airways and instrument approach procedures. The objective of this effort was to develop expertise and techniques that make use of technological advancements while improving safety, efficiency and productivity in the Canadian air transportation environment. Advancement in this area means Canada will participate in a leadership role to ensure air navigation safety.

This report presents the results of the pilot implementation of the Airspace Design System (ADS) by Virtual Prototypes Inc. (VPI) and suggests recommendations for future development of the system.

1.2 Basic Concept

The conceptual Airspace Design System is an integrated software tool implemented on a high performance 3D graphics workstation. This system provides a complete environment for computer-aided design and evaluation of flight procedures. The system stresses a user-oriented man-machine interface (MMI) approach for ease of operation by a user with no extensive computer background. Easy to use menus, immediate visual feedback and accurate graphics modeling are essential. The design specialist must be in active control of the design process. The system serves as an intelligent assistant that can take care of the technical details.

1.2.1 The Terrain Model

A terrain data base using standard format digital terrain elevation data (DTED) provides both the terrain obstacle information and data to generate terrain model graphic displays. This replaces the need for topographical maps from which the specialist derives the terrain obstacle information. The terrain model graphic displays also provide the backdrop for the procedure development and other useful visual cues.

1.2.2 The On-line Data Base

Airport data, navigation facilities as well as the man-made obstacle information are maintained in an on-line data base. This data base centralizes the information requirements for the flight procedure development process. It provides data for the flight segment computa-

tion and the graphic display symbology representation. It also provides the interactive information access. Built-in data checking is applied to data entry and data updates. A centralized on-line data base guarantees data integrity, minimizes data duplication and eliminates unnecessary cross-referencing.

1.2.3 The Expert System

The most powerful concept of ADS is the expert system that embodies the expert knowledge for flight procedure development. The rules, methods and limits laid out by the Criteria for the Development of Instrument Procedures [1], the algorithms for geodesic calculation and the graphic display generation (drafting) are integrated to form the knowledge base of the expert system.

This knowledge base is applied to the specific flight procedure parameters in determining a flight procedure. The encoded expertise of the system alleviates the lengthy computations, tedious drafting demands and eliminates the need for reference book searches. By automating the routine tasks, the expert system helps to prevent common minor errors or inconsistencies and promotes standardization of results. The specialist is therefore free to explore alternatives and solve unique problems rapidly and efficiently.

The system could also serve as a criteria development tool. By modifying the knowledge base of the system, qualified specialists could experiment with the procedure design criteria, simulating the results expected from the changes to existing criteria. The specialists could thereby verify hypotheses and gain confidence on proposed changes and additions before adopting them as standards.

1.3 The Pilot ADS

The pilot ADS implementation set out to prove the feasibility of the ADS concept and to initiate the development process of the full-scale system.

A test region was identified to limit the scope of this initial effort. This test region extends from the western tip of the Niagara Peninsula in Ontario to Quebec City in Quebec and includes areas north of the Canadian-U.S. border to the latitude of North Bay, Ontario. All the DTED, aeronautical, and obstruction data to support procedure design and development in the test region are available on-line.

The existing criteria for the development of instrument procedures including instrument approach procedures and airways have been studied to identify the domain of knowledge used by the design specialists. The Instrument Landing System (ILS) instrument approach procedure design module has been implemented as a pilot module. The ILS instrument approach procedure has been chosen for the initial implementation because it is a precision approach procedure. As such, the criteria for its design are more specific making it some what simpler to implement. It also incorporates most of the common components of any type of instrument procedure. This implementation served to test out the validity of the knowledge base approach and to develop the algorithmic computations and the graphic display generation capability of ADS.

Another objective achieved in the pilot system was to set the standard for the MMI and to provide, through a self-contained prototype of the full-scale system, a test bed for concept evaluation by the potential users. The ADS user can, through interacting with the system,

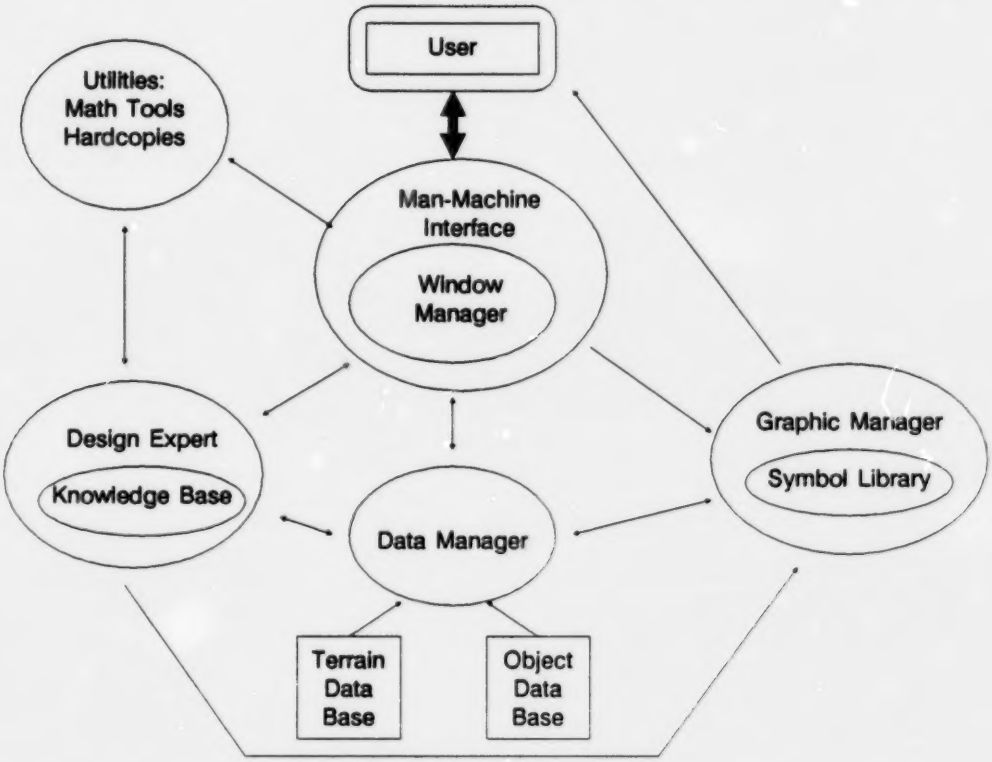


Fig. 1. ADS System Architecture.

evaluate the suitability of the MMI design and actively influence the design of the eventual full-scale system.

The ADS system architecture is shown in Fig. 1. The rest of the report will present, in more detail, each of the major system components. Section 2 compares the ADS design domain environment with the design domain environment of the manual process. Section 3 discusses the design approach of the man-machine interface. Section 4 describes the terrain data and the terrain model implementation. The on-line data base facility is described in section 5. The flight procedure design knowledge domain and the implementation of the ILS instrument approach procedure module are discussed in section 6. Other facilities available in ADS for helping specialists in their design and evaluation tasks are described in section 7. In the last section, the conclusions and the recommendations derived from this pilot project are presented.

2. FLIGHT PROCEDURE DESIGN DOMAIN ENVIRONMENT

2.1 Introduction

The flight procedure design domain is the environment in which instrument procedures are designed using the flight procedure design criteria. This design domain must provide the following information.

1. The general defined geographic area which would encompass the flight path and the associated critical airspace.

2. Terrain elevation information within the general defined area.

3. Navigation facilities available and their attributes.

4. Aerodrome or terminal area facilities and their attributes.

5. The airspace restrictions within the general defined area.

6. Significant man-made obstructions and their attributes.

All these components of the design domain must be available to the specialist to design or evaluate a flight procedure. The design domain and the design process of the existing manual system is summarized by Fig. 2.

2.2 The Existing Design Domain

In the manual process, the design domain is provided mainly by topographical charts. Topographical charts provide the terrain elevation information as well as other information such as the location of navigation aids, location and altitude of some man-made obstacles and other cultural features. These charts also serve as work sheets on which the specialist drafts his procedure design. For the purpose of enroute airway design, topographical charts of 1:500,000 scale are used. For approach and departure design, topographical charts of 1:50,000 scale are used.

There are draw backs in the use of topographical charts. These charts are published according to a standard map indexing scheme. It is often necessary to manually paste together several of these charts in order to cover the general defined area of a specific flight procedure. Since the topographical charts are of fixed scale and contain a huge amount of data, locating information from such media is not easy. In addition, as the topographical charts are published infrequently, not all the navigation facilities or obstacles are shown. It is therefore necessary to supplement the charts with information from other sources. These include other charts, supplementary publications and data bases.

The aerodrome site plan of 1:10,000 scale is used to provide information on the geographic position (latitude and longitude coordinates) of the airport reference point, the runway specifications and the position of other navigation facilities. The Designated Airspace Handbook [2] provides the description of the restricted airspace. Such airspace is defined by a set of coordinates specifying its dimensions and the effective time period. A data base maintained by Transport Canada provides a list of significant obstacles, navigation facilities and

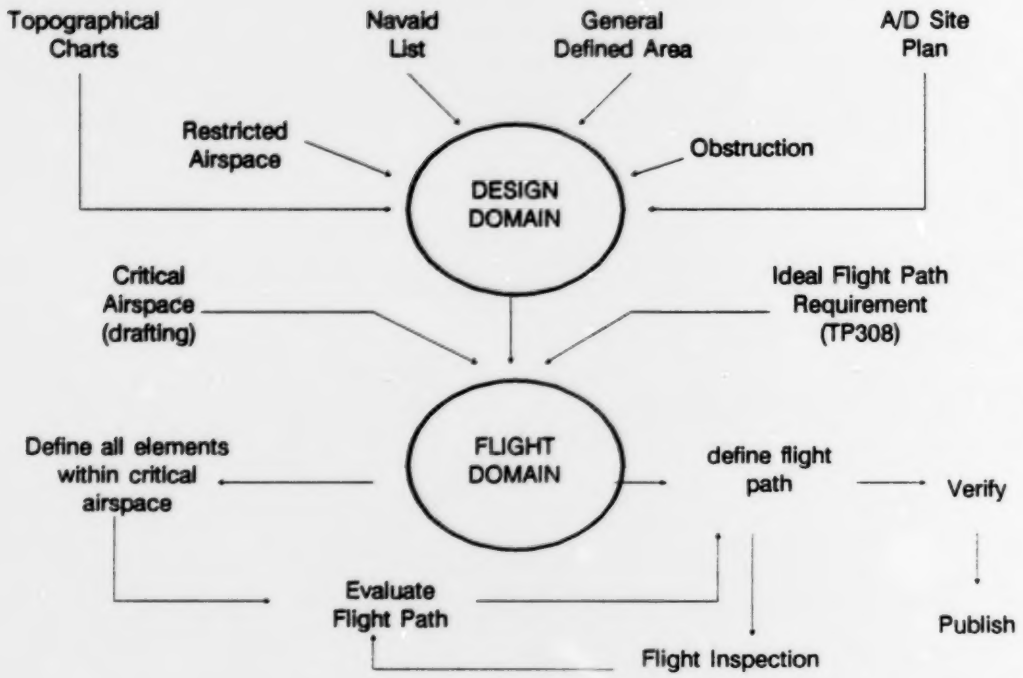


Fig. 2. Information Flow in the Manual Process.

enroute waypoints. This data base contains up-to-date information of these objects, their respective geographic positions in latitude, longitude. Attributes for obstacles also describe height above sea level (MSL) and above ground level (AGL). This information must be cross-checked with information derived from the topographical charts.

Some of the problems inherent in defining the design domain of the manual process are:

1. *Data Completeness*. Since there are multiple sources of information and these have different structures, the specialist has to make an effort to correlate these sources and make sure that all relevant information has been covered.

2. *Data Correctness*. New information and amendments must be incorporated into the design domain. Obsolete information still existing on the topographical charts must be identified and overrode. However, the present manual system depends on the ability of individual specialist to take into consideration all the ramifications of these situations and to interpret them correctly.

3. *Data Access*. Each information source requires a different data access method. For example, obtaining information from topographical charts often requires tedious searching and calculations. A specialist has to be familiar with all the different data access methods and apply them carefully.

4. *Duplication and Redundancy*. This state of affairs can easily lead to confusion and often misuse of data. It also reduces the confidence level of the flight procedure design domain.

2.3 The Design Domain of ADS

The ADS system provides the design specialist with a complete and easy to use design domain. It improves on the existing situation and provides solutions to existing problems. Some of the solutions provided by ADS are:

1. *Centralization of the information*. A centralized data base of all the relevant design domain information has many advantages. It makes the data management process easier. The information is gathered once and then kept up-to-date. This current information is provided automatically as the design domain. The specialist no longer has to go through the manual process of information gathering. This helps in improving the confidence level on the correctness and the completeness of the information.

2. *Better access methods*. Data access methods are improved by a uniform user interface. The computer takes over the routine chores of searching and checking. Better data representation methods using graphics and flexible access control also enhances the effective use of the information. Normally, graphical representation of information is more effective than textual representation. The ability to interactively control the level of detail of the information presented allow the user to focus on a subset of all information in the design domain.

3. *Emphasis on a third visual dimension*. In the design of flight procedures, the height or altitude of objects and the terrain is a critical factor. This is normally difficult to perceive two dimensionally. The ADS design domain provides three-dimensional perspective modeling of the terrain and object data which help the design specialist in interpreting critical situations.

2.3.1 The Sources of Information

In order to centralize the information in ADS, the pilot project identified the sources from which the central data base can be built and maintained. The information requirements of the design domain can be divided into two main groups of a differing nature. The first is the terrain elevation information. This data is of a permanent nature. The second includes descriptions of all the other man-made elements. These elements include objects such as navigation facilities, aerodrome features, terminal area facilities, restricted airspaces and man-made obstacles. Data for these elements are subject to change.

Digitized terrain elevation data are available in the NATO standard data format: Digital Terrain Elevation Data Exchange Format [3]. Terrain data in this format is well suited for this application. More detail on the terrain data and how they are used is described in Section 4.

Aeronautical Radio Inc. (ARINC) of the United States has proposed a specification for a navigation system data base. This specification is often referred to as ARINC Specification 424 [4]. This specification provides the standards for the airborne navigation system reference data. The nature of these navigation system reference data is quite similar to the object data requirement of the flight procedure design domain. The ADS on-line data base adopts this standard where applicable and provides conversion facilities for using data of this form. More detail on the object data is discussed in Section 5.

Since standard data formats have been adopted for the two data bases, most of the required data for creating the design domain data bases can be obtained from existing data banks. These information for the test region of the ADS pilot project has been provided by Transport Canada in these standard data formats. Restricted airspace and the man-made obstacle data, however, required special consideration.

2.3.2 The Display and Control of Information

ADS presents the design domain information to the specialist in various forms using both textual and graphic displays. For example, terrain information is presented as a two-dimensional contour map as well as a three-dimensional perspective view of the terrain model. Geographic coordinates and elevations are supplemented by textual labels. For the two-dimensional contour display, the user can control the map scale, the contour interval and move around in the general defined area. For the three-dimensional terrain model, it is possible to vary the view point and the viewing direction to obtain different perspectives.

Other objects in the design domain are represented symbolically in both the two and three dimensional displays. Objects of the same type are considered to be of the same class and can be shown or hidden as a group at the discretion of the user. A short list of all the objects of the same class within the general defined area of the design domain is provided. Textual description of the attributes of individual objects can be obtained either through this list or by selection of the symbolic representation on the contour map display. The level or amount of data shown on the display is at the discretion of the user.

2.3.3 Creating the Design Domain in ADS

The key to creating the design domain is defining the reference geographic position about which the general defined area is constructed.

Available to the user at all times is the top-level information in his region including airports, navigation facilities and enroute waypoints. Terrain data available on-line on the system will provide contour information and terrain model display in perspective. The specialist can therefore use the system control tools to move around the general defined area, viewing the design domain from different view points and with various degrees of detail and focus on the particular point of interest. With the help of these initial displays, the user can interactively focus on the reference position.

Once the reference position is defined, the system will build the design domain automatically. All the relevant local information, including obstacles, terminal area facilities and fixes that are within the general defined area will be gathered automatically and presented to the user visually. The objects in the design domain are represented graphically on both the 2D and the 3D displays. These symbologies are placed at their geographic positions relative to the map and the terrain model. In the case of man-made obstacles and runways, the 3D

graphical representations depicts the actual dimensions of these objects. The same data used to generate this visual information for the specialist will also be used by the expert system for the construction of the flight segments of the flight procedure.

The next section discusses the basic features of the man-machine interface and describes the general procedure with which the user controls the design domain environment of ADS. More detail on the control of the design domain environment is given in the ADS User's Manual.

3. THE ADS MAN-MACHINE INTERFACE

3.1 The ADS Man-Machine Interface Design

The flight design specialist interacts with the ADS through a hierarchy of menus, displays and dialogues or messages. The interaction is principally event-driven. Menus provide the access to the system functions, tools and the means to enter user input. Displays provide graphical or textual information and feedback resulting from input events. The 3D graphics capability of the graphics workstation is used to provide perspective display of the terrain model and other elements in the design domain and the flight domain. Dialogues and messages provide another means of communication between the user and the system.

Menus, displays and messages form the interface layer between the user (the design specialist) and the system components. This interface is referred to as the man-machine interface (MMI) of the system (see Fig. 1). In Fig. 3 an overview of the MMI hierarchy is given summarizing the major menus and displays. The VPI proprietary window manager is the central controlling unit of the MMI. It manages the screen in response to user events and dispatches user requests to the appropriate functional module of the system. Standard window and menu utilities are used to build the MMI. The use of these utilities ensures uniformity, consistency and ease of maintenance.

In ADS MMI design, emphasis was placed on analyzing the user tasks and the flight procedures design methods used in the manual process. The natural sequencing of tasks from the user's perspective is retained even if it meant extra work for the system. Some of the important considerations are:

1. consistency, flexibility and ease of input;

2. the logical grouping and sequencing of operations; and

3. meaningful feedback through the use of color and symbology.

3.2 The General Screen Layout

Menus, displays and messages appear in overlapping *windows* on the screen of the workstation console. These windows can be moved, resized, deleted and recalled at the user's control. A window is a rectangular area on the screen used for task specific communication between the user and the system. Two typical windows are shown to illustrate the general features. Fig. 4 shows a typical menu window with textual display fields. Fig. 5 shows a resizable graphic display window. As illustrated in these figures, each window contains two or more *panels*. Panels are designated areas within a window partitioned according to functional groupings. All the windows in ADS contain a *title panel*. The organization of the title panel for all the windows, except the *top level control menu* window, are the same. The title panel spans the top of the window. Arranged below the title panel of each window is one or more task-specific panels. Each of these panels can be viewed as a logical grouping of communication channels.

The title panel contains a *title bar* and a *kill icon*. For graphic display windows which are reshapable, there is also a *reshape icon*. The title bar, besides identifying the function of

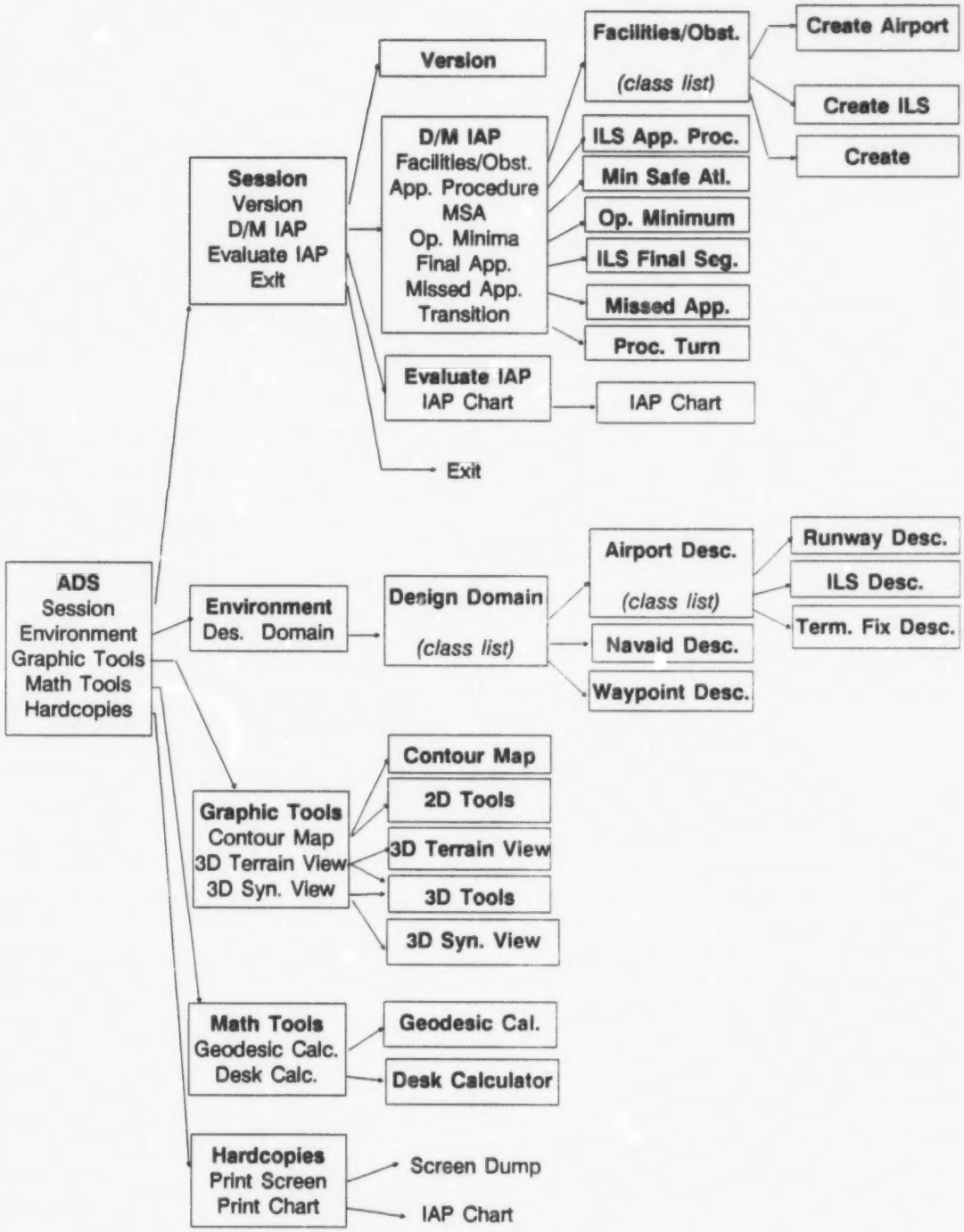


Fig. 3. Man-Machine Interface Hierarchy.

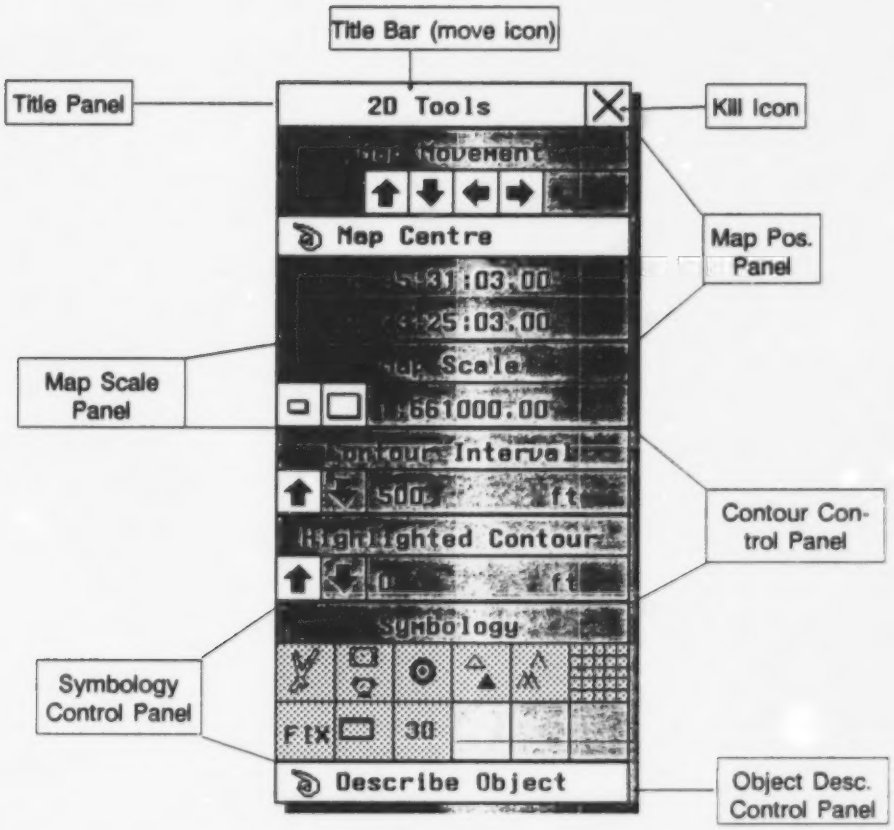


Fig. 4. 2D Tools Menu Window.

the window, serves as a move icon. Through the control of these icons in the title panel, the user can organize the screen layout.

The top level menu window is a special case. This window is always present during an ADS session. It provides the direct entries to the major system function menus and displays. The layout of this window is slightly different from all the other windows. To the left is the title bar containing the acronym ADS. The title bar serves also as a *move icon*. Since the top level menu is always present, there is no *kill icon*. To the right of the title bar is a panel containing the names of major system functions. Each function name is an icon providing access to a pull-down submenu of the functions of that function group. Fig. 6 shows the top level menu window with the "Hardcopies" submenu pulled down and the "Print Screen" icon highlighted. During an ADS session, depending on the current task the user is engaged in, all the pertinent windows in the MMI hierarchy will be accessible to the user through screen interaction.

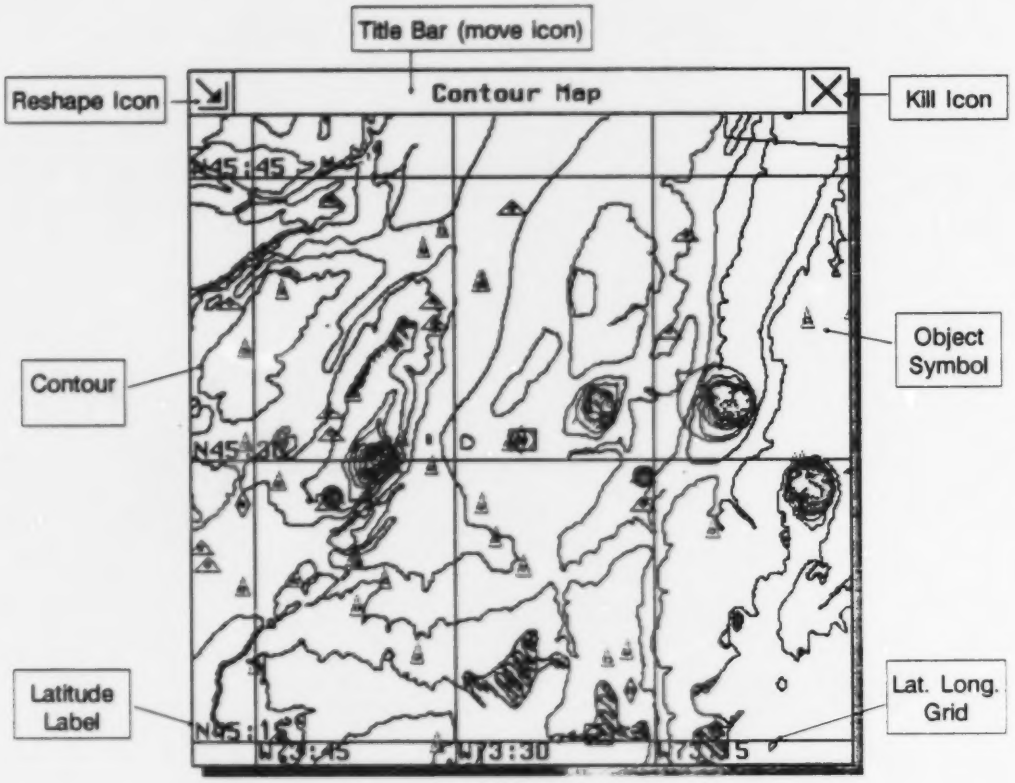


Fig. 5. Contour Map Display Window.

Fig. 6. Top Level ADS Menu Window.

3.3 Window Functions

The ADS MMI is built on *menus* and *displays*. Menus represent input communication channels as displays represent output communication channels. A menu window contains groups of available functions and options and permits the user to specify control by selecting them. System functions or options are represented by *function icons*. A function icon is a well-

defined area inside the window within which the function can be activated. A menu is a group of such function icons.

Within a menu window, there may be one or more menus. Some menus have associated textual displays. The display may serve to clarify or supplement the task represented by the menu. It is convenient to combine the menu-display group in a panel. In Fig. 4 the partitioning of the 2D Tools menu window into panels is shown. For complex tasks, which can be broken down into subtasks, menu provides the entry point to submenu windows. The use of a hierarchy of menu windows provides separation of functions and limits the number of options to be considered at any one time.

As an output communication channel, a display window provides an area of the screen where information is conveyed to the user. A display window can display text or graphics.Graphic display is usually a more compact form of information representation. By using established symbology and meaningful color schemes, information such as type, density, magnitude or relative position can be conveyed without lengthy description. The main graphic displays in ADS are the 2D and 3D displays of the design domain. To add flexibility to the screen layout, graphic display windows are reshapable.

Text displays are used to display attribute description or numeric values. Examples of text displays are descriptions of objects in the design domain and the ILS procedure design summary. Scrollable displays allow relatively large amounts of text information to be shown in a relatively small window area. The information provided by a display can be controlled through menus. For example, the 2D Tools in Fig. 4 provides control over the Contour Map in Fig. 5.

3.4 User Input Events

The user controls ADS by interacting with the MMI of the system. Most of the interactions are carried out through the screen by generating input events. The user interacts with the system for a variety of reasons. In general, a user input event is either to effect some control function or to enter data values. Some of the specific reasons for an input event are:

- to activate a system function;
- to choose an option;
- to select a mode of operation;
- to provide or modify the value of a system variable or a function parameter;
- to request information;
- to enter information.

ADS has two input devices: the *mouse* and the *keyboard*. Except for starting a ADS session and for keyboard data entry, all the control functions and other data entry modes are effected through the use of the mouse. The mouse is an optical input device that allows the user to manipulate the cursor position on the screen. The user can issue signals to the computer by operating the mouse buttons. The mouse used in ADS is a three button mouse. The right button is the normal working button. The middle button is reserved for an on-line help facility to be developed in the future. The left button is currently unused.

The user effects an input event using the mouse through the following operations:

1. *Move the Mouse.* Slide the mouse on the mouse pad without pressing any button. This action moves the position of the cursor on the screen.

2. *Click a Button.* Hold down a button, then quickly let go of it without moving the mouse. This action sends the current position of the cursor to the system.

3. *Press a Button.* Hold down a button for a desired duration. This action, in addition to sending the current position of the cursor, also provides a magnitude value through the length of the duration.

4. *Drag the Mouse.* Move the mouse while pressing on a button. This action indicates a direction of movement or a vector value.

5. *Release a button.* Let go of the button that has been pressed. This action terminates an input event.

Using mouse activated menus provides a robust and effective method of input. It minimizes the need for memorizing and keying in lengthy or complicated commands. To illustrate how the user operates the ADS MMI, the screen layout control functions are described below. Other input events are made by similar use of mouse operations.

1. *Moving Windows Around.* To reposition a window, move the mouse to position the cursor inside the move icon, then drag the mouse using the right button. This will cause an outline of the window to follow the cursor as it is being dragged. On release, the window will be moved to the new position.

2. *Reshaping Windows.* To change the size of a reshapable window, move the mouse to position the cursor inside the reshape icon. Again, by dragging the mouse using the right button, the window size can be reshaped within the allowable limits.

3. *Deleting Windows.* To make a window disappear from the screen, move the mouse to position the cursor inside the kill icon. Clicking the right button will make the window disappear temporarily. The window can be recalled by reselecting it from the appropriate menu.

4. *Popping Windows.* A newly added window will always be on top of other windows on the screen. To bring any partially covered window to the top, move the mouse to position the cursor anywhere within that window and click the right button.

The keyboard is another input device. It is most suited for textual data input. When this form of input is required, the user enter the data by typing on the keyboard. ADS provides a data entry window to display the data entered by the user.

3.5 Visual Feedback

When the user makes a request through the MMI, it is important that the system give immediate feedback of some sort to acknowledge the receipt of an input event. Normally if the user request leads to some immediately visible system change, no additional feedback is required. However this is often not the case. In such cases, standard methods are used to provide visual feedback to the user:

1. *Cursors Change.* Different cursor symbols are used to indicate different modes of the system. By displaying a different cursor, the system indicates a change of mode. Fig. 7 summarizes the cursors used in ADS and the modes they represent.

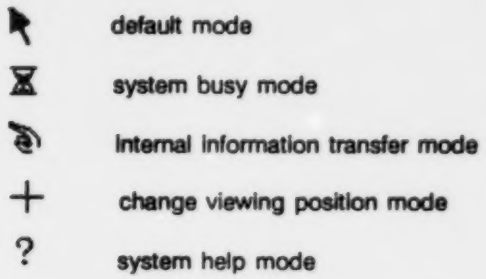


Fig. 7. Cursor Symbols.

2. *Icon Highlight.* Icons represent functions or options. Highlighting an icon is achieved by displaying it in a visually different manner. The currently selected function or object and the currently active options are highlighted to make them stand out. On the other hand, icons of functions that are temporarily unavailable are shaded to reflect this state.

3. *Messages and Confirmations.* Where the situation warrants, the system will display error report, action report or confirmation messages in response to user events as extra help in communication.

Beside these reactional feedback methods, ADS makes use of color codes and symbologies to enhence visual communication:

1. *Color Code.* As an illustration, the window manager uses a color scheme with 3 colors. The different areas of a menu window are color coded to provide consistent visual separation of functions. All selectable areas (available function icons) are displayed in window background color; all unselectable areas are in window shade color; and all text and graphic icon labeling are in window foreground color. These colors corresponds to blue, grey and white on the screen display (and represented on paper as white, grey and black respectively in the figures shown in this report).

2. *Symbology.* Where appropriate, symbols are used instead of text. As illustrated in Fig. 4, symbols are used to label the function icons. Graphic symbols usually convey information visually more effectively than text.

4. TERRAIN DATA

4.1 Use of Terrain Data in ADS

The manual process of designing approach procedures relies heavily on the use of paper topographical maps to position the flight segments, search for maximum elevations, evaluate obstacle clearance, etc. In ADS, the paper maps have been replaced by Digital Terrain Elevation Data (DTED). The DTED are essentially terrain elevation samples taken at regular intervals in machine-readable form.

These elevation samples are used internally by ADS. Searching for the maximum elevations within a region or determining the altitude of a navigational facility when no other data is available are two examples of such use. The DTED are also presented graphically to the user in the form of a contour map and as a three dimensional perspective terrain model.

4.1.1 Contour Map

The contour map provided in ADS is similar to paper contour maps with a few notable differences. The most important difference is that the contour map may be viewed by the user at any arbitrary scale between 1:10,000 and 1:1,000,000. The accuracy of the contour map, however, is always limited to the accuracy of the DTED used in producing the map, regardless of the scale at which the map is viewed.

The altitudes of the various contour lines are denoted using a coloring scheme. The color of each line varies from a dark green at the lowest altitudes to a bright yellow (almost white) at the highest altitudes. The user can obtain more specific altitude information by selecting the contour lines of a particular altitude and highlighting them using the contour control functions in 2D Tools (Fig. 4). Labeling of individual lines as in paper maps was not done due to the arbitrary nature of most labeling schemes which cannot be easily adapted to computers. Furthermore, given the smallest font available, labeling the lines would have caused unnecessary clutter.

The contour map is also annotated with the positions of all known navigational aids, obstacles, aerodromes, etc. The position of each of these objects is denoted by a standard symbol of a particular color. The symbols on the map are not labeled. However, a description of a symbol can be called up. This can be achieved by clicking the "Describe Object" icon of the 2D Tools and then clicking the symbol to select it. Place names and other cultural features such as hydrology, roads, etc. are currently not shown on the map. Such information could be implemented as a separate layer over the contour map. This would involve adding the data for such information to the design domain data base.

4.1.2 3D Perspective

The 3D perspective model allows the user to view the terrain data in three dimensions. The 3D model is an approximate representation of the terrain generated by spreading an artificial surface over all of the sample elevation points. Although the resulting image is not 100% realistic, it provides a fairly accurate representation of the salient features of the terrain.

As in the contour map, three dimensional symbols are shown spatially correct in the 3D view to represent the known navaids, obstacles, etc. These 3D symbols are not necessarily accurate replicas of the objects they depict. The critical airspace of the flight paths defined by OCS (described in Section 6.5) are shown in the 3D view as adjoining planar surfaces.

The 3D terrain model can be viewed from any arbitrary point in space and from any angle. This allows the user to visually inspect any problem areas such as the penetration of the OCS by an obstacle or the terrain itself. The 3D terrain model provides a superior method of data validation by presenting a picture of data incompatibility. Problem areas which would not normally be found became evident in the 3D perspective view.

4.2 Data Format

Three sets of files are used for the terrain model. These are the DTED files, the contour files and the 3D files. The contour files and the 3D files are generated from the DTED.

4.2.1 DTED Files

The DTED used in ADS is in the standard format described in [3]. This format makes provisions for two data density levels called Level 1 and Level 2. In Level 1 data, the elevation samples are spaced three seconds of latitude arc apart, whereas in Level 2 they are spaced one second of latitude arc apart. In both cases, the longitudinal spacing between the samples depends on the latitude of the data due to the merging of the longitudinal lines at the poles. The spacing increases in the direction of the poles, going from every 3 seconds at the equator up to every 18 seconds at either pole in the case of Level 1 data.

ADS only makes use of the Level 1 data. Level 1 data comes in files which cover a 1°x1° area. Elevations are given in integral number of meters with respect to Mean Sea Level (MSL). Within the test region samples are every 3 seconds in both latitude and longitude. Thus DTED files for the test region contain 1,442,401 samples arranged in 1201 columns of 1201 elevations. This results in approximately 2.8 megabytes of disk space for each file.

4.2.2 Contour Files

The data for the contour map are stored in files covering 12 minutes by 12 minutes. Each of these files is known as a *superblock*. Each superblock is further subdivided into blocks covering 3 minutes by 3 minutes. Each block contains a series of line segments grouped together by elevation. The vertical distance between contours is arbitrary, although 50 ft is the standard contour interval used within the test region.

The size of individual superblock files will vary greatly depending on the contour interval used and the flatness of the terrain being mapped. Within the test region, contour files are anywhere between 14 kilobytes up to 600 kilobytes.

4.2.3 3D Files

The data for the 3D view are stored in files covering 6 minutes by 6 minutes. Each of these files is also known as a *superblock*. Each superblock is further subdivided into blocks covering 18 seconds by 18 seconds. Each block contains the Binary Space Partitioning Tree (BSP tree) (described in Section 4.3.3) of the polygonal representation of the terrain. Each superblock file contains a table of common vertices and a table of common normals.

The size of the 3D files also varies greatly, ranging anywhere from 150 kilobytes up to 1.5 megabytes.

4.3 Terrain Modeling Methods

In order to calculate the elevation of any arbitrary point or to draw the terrain in three dimensions given DTED samples every three seconds, it is necessary to approximate the terrain surface in between the sample points.

A very simple approximation consists of connecting four adjacent sample elevations (forming the four corners of a square) using a flat surface. This is not possible, however, when the four points do not lie on the same 3-dimensional plane. To avoid this problem, an intermediate elevation point is introduced at the center of the sample points by averaging the

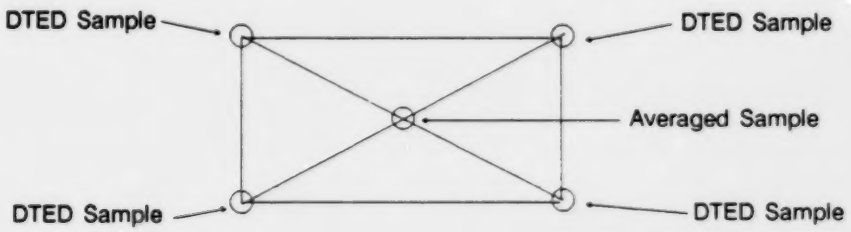


Fig. 8. Terrain Model.

elevations of the four corners. It is then always possible to connect the four corners to the center elevation using four triangles as shown in Fig. 8.

Note that these triangles are 3-dimensional, i.e. each vertex is located at a particular latitude, longitude and elevation, and represent a continuous surface in space between the vertices. This model is used as the basis for all elevation calculations, the contour map and the three-dimensional view of the terrain.

4.3.1 Elevation Evaluation

When the elevation of a specific point on the terrain is required, this information is computed from the DTED in the following manner. The point can either be a DTED sample point or it must lie between four sample elevations as shown in Fig. 8. and will therefore lie inside one of the four triangular areas. The plane equation of the triangle in which it lies can then be used to calculate the elevation of the point.

4.3.2 Contour Map

Producing contour lines from the standard terrain model is a fairly simple, albeit a computationally expensive, procedure. Each terrain model triangle is successively sliced using horizontal planes at fixed intervals. Each intersection of a triangle and a horizontal contour plane defines a line segment which is then added to a list of all the line segments produced by the same horizontal plane.

Keeping the line segments sorted by elevation allows each set of line segments to be colored according to elevation or to be dropped from the map display altogether when attempting to declutter the map.

4.3.3 3D View

To display the terrain model data graphically in 3D perspective view, there are two main technical problems to be resolved. The first is to provide a color scheme for displaying the polygons that represent the terrain surface. The second is to find a hidden-surface removal algorithm that allows the viewing of the terrain data and other 3D object modeling data in a coherent manner.

In an actual photograph, relief features of terrain are visible due to textures, reflections and shadows on the surface of the terrain surface. It is, however, not feasible to reproduce such complex visual cues using the hardware available. To show the salient features of the terrain, a simple lighting model based on the slopes of the polygons of the terrain model is used. The same color is assigned to all the polygons initially and then the shade of the color is varied according to the following scheme. The terrain is assumed to be a shade of green with certain reflective properties. Ambient light is added to make all of the terrain initially visible. Infinite light sources are then positioned parallel to the horizon coming from the north, south, east and west. Having four light sources instead of a single overhead source such as the sun, although not very realistic, provides better contrast when viewing the terrain. The initial color of the terrain, its reflective properties, the ambient light and the angle of reflection between the polygon and the four light sources can then be used to calculate the final color for each polygon. This provides a fairly intuitive variation in the shading which provides sufficient visual cues to give a 3-dimensional depth to the picture.

The hidden surface removal problem concerns the display of objects that are overlapping with respect to the current view point. Intuitively this can be solved in the following manner. When drawing several overlapping objects (or several surfaces of a single object), each object (or surface) must be drawn after the objects (or surfaces) that it obscures. Although there are many algorithms for computing this correct drawing order, most are very expensive computationally and cannot be used for real-time viewing of a scene.

One of the fastest algorithms suitable for real-time or near real-time viewing of 3-dimensional objects is the use of BSP Trees [5]. Simply put, this algorithm involves repeatedly cutting up the original polygons until a single pre-ordered list can be formed which will work for all viewpoints. This special pre-ordering obviates the need to re-order the polygons for each new viewpoint as most other algorithms do. Although the original BSP algorithm is limited to static world models, it has been extended to include moving objects within the static world. This extension was necessary to allow the display of OCS's, runways, waypoint markers, etc. along with the terrain. The major disadvantage of this algorithm, however, is the large disk space it requires. The original DTED will in general expand to at least ten times its size after conversion to BSP Trees.

4.3.4 Projections

Another question that always comes up in displaying geographic information is the choice of projection. Different projections preserve different relationships such as latitude-longitude measurements, directions, great circles, areas, etc. If a map is to be used to take such measurements, the projection used will greatly affect the accuracy of these measurements.

Furthermore, the inaccuracy of these measurements usually increases with the scale of the map.

In ADS all measurements such as arc lengths, bearings, etc. are calculated using a mathematically derived earth model based on the Clarke 1866 ellipsoid datum. The choice of projection then becomes more a question of aesthetics and ease of implementation rather than one of accuracy. Given the small areas normally displayed in ADS, the distortions found in simpler projections are insignificant. Therefore the simplest projection, the *cylindrical equidistant projection* has been used.

In a cylindrical equidistant projection, the lines of latitude and longitude are equally spaced to form a rectilinear grid. The latitudinal and longitudinal scalings are calculated at a particular latitude known as the standard parallel and are kept constant throughout the map. In ADS the standard parallel is chosen to be at the centre of the general defined area of the design domain. This projection is used in displaying both the contour map and the 3D perspective view. In the 3D view, this implies that the terrain does not follow the curvature of the earth, but given the restricted visibility of the 3D view (2.5 km), this limitation is not noticeable. Note that the cylindrical equidistant projection does not work at the poles.

4.4 Data Management

In the pilot system, the management of all the terrain data files is chiefly the responsibility of the user. In a more developed version of ADS, most of the data management could presumably be automated. Before starting an ADS session, the user must ensure that all the necessary DTED files and their corresponding contour map and terrain files are available on disk.

All of the DTED files for the test region are archived on cartridge tapes. Anywhere from one to four DTED files must be extracted from the tapes to cover the general defined area of the design session. If there is insufficient room on the disk for storing the new DTED files, it is up to the user to delete old files which are no longer of interest to make room for the new ones.

The contour map and 3D terrain files must be generated from the DTED files using ADS utility programs. The contour map files are generated using the *genmap* utility, whereas the 3D terrain files are generated using the *genter* utility. The procedures for using these two utility programs are described in the ADS User's Manual.

Using the current hardware, extracting the DTED files from tape can take anywhere from 5 to 15 minutes per DTED file. Generating the contour map takes approximately 10 minutes per DTED file while generating the 3D terrain files takes another 50 minutes per DTED. The generation times will vary depending on the flatness of the terrain.

5. OBJECT DATA

5.1 Object Data Classes

Beside the terrain information, the design domain contains information on other man-made elements. These elements, referred to as design domain objects, can be grouped under classes according to their commonality.

1. Global Object Classes. These include aerodrome facility (airport), VHF navigation systems (such as VOR, DME etc.), LF navigation systems (such as NDB) and enroute waypoints.

2. Terminal Area Object Classes. These include runways, Instrument Landing Systems (ILS) and terminal fixes.

3. Local Object Classes. These include the restricted airspaces and man-made obstructions.

The design domain objects are grouped under these classes for the purpose of organization and access. Within an object class, the objects are treated uniformly. Each object class is associated with a 2D and a 3D symbolic representation for the graphic displays. As far as possible, the normal navigation symbols are adopted. Where such symbols are not available, new ones have been invented.

Associated with each object of any class is a geographic position. This geographic position is used to place the object in the graphic displays. For each object class there are additional attributes to describe the individual domain object. As an example, a runway object description includes the runway bearing, the runway length and width, threshold displacement and the elevation at the runway threshold as well as other attributes used in the flight procedure design process. Another example is a restricted airspace object which is described by its dimension, the restriction type, and the time period it is in effect.

5.2 Data Sources

Both the global object classes and the terminal object classes concern objects common to other air navigation systems. Information on these objects was supplied as data in the ARINC Specification data exchange format [4] and are stored in a file using this format.

The man-made obstacle information was provided from a data base in Transport Canada. The initial obstacle data in the test region of the pilot ADS is supplied in this data base format. This information has been converted and stored in a file using a special ADS format.

For the restricted airspace data, there is no machine readable data base available. The initial data was extracted manually from the Designated Airspace Handbook [2] and stored in a file using a special ADS format.

5.3 Data Organization and Management

For the pilot ADS, all the object data are grouped under the pilot project test region. Since, this data base is relatively small and to save time, no elaborate file management mechanism

has been developed. The data are loaded and stored in memory as required for efficient access. At the end of an ADS session, all the data are written back on files.

5.3.1 Top Level Object Data

At the start of an ADS session, data for the global object classes and the terminal area object classes of the test region are loaded into the system. These objects are accessed through reference pointers. Reference pointers to objects of the same class are stored as linked lists. A table of these object lists is maintained. For each airport object, there are also reference lists to the terminal area objects associated with that airport. These separate lists provide means of direct access to the object data through different access routes.

5.3.2 Design Domain Object Data

When a design domain is defined, short lists of the objects which fall within the general defined area of the design domain for each of these classes are extracted. In addition, the data for the local object classes: the restricted airspaces and the man-made obstacles, are loaded. The corresponding reference lists are constructed. A table of access to these design domain lists is also created.

5.4 Data Usage

The data base provides for both internal data access by the system and interactive data access by the user.

5.4.1 Internal Data Access

The system uses the on-line data base in different ways to perform the various system functions.

1. All top level objects and design domain objects can be displayed on the graphic displays under user control. Each object class is treated as an independent layer in the graphic display. The user controls whether or not a particular object class is visible. The system builds the graphic displays by drawing the visible layers using the information in the data base.

2. During a flight procedure design, the system needs to know flight domain parameters such as the geographic location and characteristics of navaids and the runway specifications. These parameters are used to compute the ideal flight path and to construct the protected airspace around it. These flight domain parameters are derived from data in the data base.

3. Where the flight procedure design summary and the IAP chart provide information on the design domain objects, the information is also provided by this data base.

5.4.2 Interactive Data Access

The on-line data base is available for interrogation at any time during an ADS session. This interrogation may be for the purpose of finding out about information stored in the data base. It may also be for redirecting the information to specify the flight domain parameters that the system needs for the design process.

For the purpose of information retrieval, the user can select the object of interest from a menu containing a short list of objects of that class or by clicking at the graphic symbol on the contour map display. The system will provide an object description by means of a display window.

Redirection of data as input parameters are accomplished using mouse operations. By selecting the destination and then the input item, internal data transfer functions will effectuate the transfer of the selected information. This data redirection method is easy to use and also eliminates unnecessary duplication of data entry and verification.

5.5 Data Base Update

An object in the data base can be considered to be permanent or temporary in nature. Permanent objects are real, existing objects. Normally the user should not modify these data unless an official change through the Air Information Regulation and Control NOTAM has occurred. However, during an ADS session, the user may need to create and modify temporary object data. These data of temporary nature may be necessary for the procedure design process to represent change or addition. These must be distinguishable from the permanent data until they are officially established.

ADS allows the user to interactively create new objects and update or delete existing objects. This facility is provided through a set of data entry menus. A specialized menu is provided for each object class. Data checking is built into this data entry interface to provide data validation at the source level.

For the pilot project, object data with the exception of restricted airspace can be edited by the user during an ADS session. At the end of a session, the current on-line data base is stored back on disk. For the moment, there is no distinction between data of a permanent or temporary nature. No attempt to preserve the state of the data base is provided beyond keeping a backup copy of the previous data base. It is, therefore the responsibility of the user to maintain the integrity of the data base.

5.6 Future Development

As it is, the object data base of the pilot ADS system achieved the goals to centralize information, to provide better access method and to provide 3D graphics visualization. However it leaves room for much improvement in several directions.

1. *Refinement of the class attributes.* In the pilot project, the class attributes used are generally those specified by ARINC. This meets the needs of the pilot project. A more careful definition of class attributes is needed to meet the future needs of a centralized data base.

2. *Extension of the data base to the rest of Canada.* The current data base must be extended to cover the whole Canadian territory. Improved data update and control procedures will be needed. This extension must also be able to handle the distinction of permanent and temporary data.

3. *Extension of the data base to include additional object classes.* Besides design domain objects, the centralized data base should be extended to include objects generated by ADS including flight segments, charts and reports. This will facilitate the review, evaluation and modification of the elements.

6. FLIGHT PROCEDURE DESIGN EXPERT SYSTEM

6.1 The Expert System Approach

Instrument flight procedures are procedures followed by pilots navigating aircrafts from point to point to achieve safe, regular instrument flight operations. Instrument flight procedures can be roughly separated into terminal procedures and enroute airway procedures. Terminal procedures are concerned with safe and efficient operation during the transition between the airborne state and the ground state. Terminal procedures require consideration of low altitude flying. Instrument approach procedures belong to this category. Enroute airway procedures ensure safe operation while the aircraft is airborne at high altitudes enroute from one destination to another. The core of ADS is an *expert system* (ES) that can be used to design these instrument flight procedures.

6.1.1 The Expert System

A simple definition of an expert system is a computer program that embodies the expertise of one or more human experts in a specific domain and applies this knowledge to make useful inferences for the user of the system. Domain expertise includes facts and figures as well as rules and procedures which uses them. The rules, facts and any other information needed to endow the program with expertise is stored in a *knowledge base* (KB).

The steps involved in developing an ES are outlined below.

1. *Identification.* Determine the problem characteristics, objectives and suitability.

2. *Conceptualization.* Define the concepts to represent knowledge and specify subtasks, strategies and constraints. For ADS, this involves identifying the flight procedure design process and the design criteria to be applied for each step of the process.

3. *Formalization.* Design structures to organize the knowledge and the control.

4. *Implementation.* Formulate the knowledge into a set of rules and associated control structures that define a prototype program capable of being executed and tested. This process is usually called *knowledge engineering.*

5. *Testing.* Validate the rules that embody the knowledge. Evaluate the performance of the prototype with respect to the correctness, consistency and control strategy. The result of testing may lead to the reformulation of rules and control processes, the redesign of the knowledge structure, and the possible redefinition of the problem's scope and goals.

6. *Refinement.* Repeat the cycle of formalization, implementation and testing.

6.1.2 The Knowledge Domain of Flight Procedure Design

The ADS ES applies expert knowledge to help its user define, construct and evaluate the components of a flight procedure. The ES verifies the specifications, performs the required obstacle clearance search and produces the minimum descent altitudes. The knowledge used includes rules on the design process and rules on the design parameters. In the

manual process, design criteria are stipulated by [1]. This document therefore represents a condensed form of knowledge for designing instrument flight procedures. This source of knowledge is incomplete in the following sense:

1. The criteria are designed for interpretation by human designers, therefore some of the rules are represented in the form of tables and graphs. This serves as graphic aid to the designer instead of providing the actual mathematical formulae or derivations.

2. The present criteria has evolved since the 1940s. The reasoning behind why certain rules and limits exist has become obscured over the years. In addition, the state of the art of both ground and airborne equipment and capabilities have changed significantly. It is not clear if some of the original limitations still apply.

3. In situations where design problems may be resolved by more than one optional solution, the criteria presents the options. However, it does not provide expert knowledge about choosing among the possible options.

Studies carried out in the ADS pilot project indicated that the problem of instrument flight procedure design is suitable for applying the expert system paradigm. The scope of the problem is too vast to be completely covered within the mandate of this pilot project. In the pilot project, the design process of ILS instrument approach procedure is used to explore a subset of the knowledge domain and to start the prototyping process. Knowledge for the initial KB is extracted from the existing criteria for the manual design process as documented in [1] and supplemented by the ICAO document PANSOP [6].

The next few sections summarize the conceptualization of the general process involved in instrument flight procedure designs as a result of the pilot study.

6.2 Instrument Approach Procedure Design

An important category of terminal procedure is instrument approach procedures (IAP). An IAP takes an aircraft from enroute altitude to safe landing or, in an missed approach situation, back to safe enroute altitude through a series of flight segments. Each flight segment has an ideal flight path or approach track, one or more segment areas for obstacle clearance analysis and the minimum descent altitudes for safe operation along the approach track. These flight segments include initial approach segments, immediate segment, final segment, circling areas and the missed approach segment.

The general design process for IAP can be divided into two main tasks: determining the design domain, and developing the flight segments. Determination of the design domain is achieved by collecting the required information which include ground and air obstructions, the aerodrome specifications, the navigation facilities, the limitations and special considerations. Flight segment development involves the establishment of the initial approach segment, the intermediate segment, the final approach segment and the missed approach segment.

There are common design factors for these flight segments:

1. *The geographic location and terrain characteristic around the aerodrome area.* In precipitous terrain, the required obstacle clearance (ROC) is usually higher.

2. *The presence of ground and air obstructions.* Obstructions influence the ideal flight path and the allowable minimum descent altitudes of operation.

3. *Category of aircraft operation.* Aircraft speed affects descent gradient and turn radius of operation.

4. *The characteristics of navigation facilities available.* System accuracy of the navigation facility affects the required obstacle clearance in the critical airspace around the ideal flight path.

A segment is established by the following steps:

1. Define the approach track (the ground projection of the ideal flight path) of the segment.

2. Determine the critical segment areas (primary, secondary, transitional, etc).

3. Establish the obstacle clearance within the critical segment areas.

4. Establish the minimum descent altitude (MDA) of the approach segment by considering the obstacle clearance and the descent gradient.

If obstacle clearance or other criteria cannot be established, then the approach track has to be modified and the process repeated until a satisfactory result is obtained. Once the different flight segments have been designed, the continuity of the approach procedure during the transitions between the flight segments must be considered.

The establishment of the visual manoeuvring of an IAP involves the following steps.

1. Determine the circling areas by considering the aircraft category and the runway alignments.

2. Establish the obstacle clearance of the circling areas and determine the MDA for each aircraft category.

3. Qualify the results established by obstacle clearance considerations to take into account other global factors. Certain sectors of the circling area may have to be eliminated.

The establishment of the minimum sector altitudes (MSA) again involves the establishment of obstacle clearance in a defined area immediately surrounding the aerodrome site.

After all the MDA of the different flight segments have been established, the operating minima for the straight-in approach and for circling is established accordingly.

6.3 Enroute Airway Procedure Design

As for the IAP, there are common design factors for enroute airway procedures:

1. *The terrain characteristic around the enroute flight path.* In precipitous terrain, the ROC is usually higher.

2. *The presence of natural and man-made obstructions.* Obstructions influence the the allowable minimum descent altitudes of operation.

3. *The flight level* . High altitude airways or those above 18,000 ft are not assessed against terrain with presently one exception.

4. *The characteristics of navigation facilities available.* System accuracy of the navigation facility affects the required obstacle clearance in the critical airspace along the enroute flight path.

The general process in the development of an enroute airway starts with the determination of the design domain characteristic including the terrain elevation, the man-made obstructions, the navigation facilities and special considerations such as precipitous terrain. The Minimum Enroute Altitude (MEA) and the Minimum Reception Altitude (MRA) of the airway are then established using the following steps:

1. Define the ideal flight path of the airway.

2. Determine the system splay area depending on the system characteristics of the governing facilities.

3. Determine the protected enroute obstacle clearance areas (primary, secondary and turning areas) of the airway.

4. Establish the obstacle clearance within the critical segment areas.

5. Establish the Minimum Obstacle Clearance Altitude (MOCA) based on the obstacle clearance result.

Depending on the established altitudes and those of adjacent airways the ideal flight path may have to be modified and the process repeated until a satisfactory result is obtained.

6.4 Determination of Obstacle Clearance

The most important step in the design process of flight procedures is the determination of the obstacle clearance within the critical areas around the ideal flight path. The critical area can be visualized by imagining a set of adjoining planar surfaces below the ideal flight path. These planar surfaces are inclined at some slope relative to a horizontal ground plane. The segment areas of a flight segment are projections of these planes onto the ground plane. These planes describe a safety net below the flight path and are referred to collectively as the obstacle clearance surface (OCS) over the segment areas. The distance between the flight path elevation and the OCS at any point is the allowed obstacle clearance at that point and must be not less than the ROC. In any design, the objective is to ensure that there is no violation of the OCS or that the ROC is preserved.

In ADS, the determination of obstacle clearance is done automatically by the expert system using information based on the terrain data and the on-line obstruction data. Depending on the type of flight segment concerned, the method for determining the obstacle clearance is slightly different.

6.4.1 Obstacle Clearance By Means Of OCS

For precision segments including the ILS final approach segment and the missed approach segment the ideal flight path is precisely defined. This means that the expected altitude along the approach track is well-defined. It is therefore possible to determine the OCS over the segment areas from the approach track specification and the ROC along the track. Obstacle clearance is established by making sure that no obstacle within the segment areas penetrates the OCS.

6.4.2 Obstacle Clearance By Means Of Minimum Obstacle Clearance Altitude

The initial approach segment and the intermediate segments are non-precision segments. For these flight segments the altitude of the actual path along the approach track is not predetermined. The process of determining the obstacle clearance proceeds by searching for the highest, or controlling obstacle in each segment area. The minimum obstacle clearance altitude (MOCA) is then determined by applying the ROC to each controlling obstacle. The MOCA determines the altitude of the OCS and the MDA of the flight path.

6.4.3 Collision Risk Model

An alternative method to assess the obstacle clearance of a flight segment is to perform collision risk analysis on the flight segments. A Collision Risk Model (CRM) has been developed by ICAO. The CRM is a mathematical model based on statistical data for computing the collision risks of precision segments such as the ILS final segment and the missed approach segment. This model can be extended to assess the collision risks of other instrument flight segments. Since the CRM assessment and the flight procedure design process share a lot of common information, both in the design domain and in the flight domain, it is logical to incorporate the CRM in ADS as an evaluation tool. Study into this possibility in the ADS pilot project indicated that it is feasible to incorporate CRM assessment into the ADS design environment. Due to resource limitations, the CRM has been omitted from the pilot implementation of ADS.

6.5 The ADS Expert System Paradigm

The ADS ES is based on a hierarchical network of action paradigm. To illustrate the working of the ES, ADS can be viewed as a *design expert* who supervises the design of ILS approach procedures. It achieve that goal by calling upon sub-modules to design the individual approach segments and to determine the circling procedure, the operating minima and the MSA. Each approach segment has an associated *segment expert*. These segment experts call upon the *critical airspace expert* and the *obstacle clearance expert* to determine the specification of the approach segment. The human designer plays an integral part in the design process by interacting with the system through the MMI to provide the required flight parameters and to control the design process.

Knowledge in ADS is represented by rules. A rule has the general form:

IF < *precondition* > THEN < *action* > .

Preconditions describe the premise based on which the associated *actions* must be taken. These preconditions are predicated upon established facts, the *current state of the system* and *user input events*. Actions are procedures to be followed when a precondition is met.

An action can be a procedural operator that achieve a specific goal, a simple updating of the current state of the system or an invocation of a subgoal.

The current state of the system is described by the current values of the system variables. These system variables include such information as the flight domain parameters and the progression of the design process in a flight procedure design. The current state of the system is stored in a depository of temporary data called the *working memory* . The working memory can be viewed as the short term memory of a human being as compared to the rules which can be viewed as the long term memory or the cumulative knowledge of the individual. The user input event is an important control structure of the ADS ES. The flight procedure designer directly influences the design process by providing input events through the MMI.

Reasoning or *inference* is achieved by drawing conclusions on the situation as registered in the short term memory and based on the knowledge in the long term memory. The fundamental difference between a rule based ES and a traditional procedural system is its ability to reason. At the heart of the ES is the *inference engine* (IE). The IE is a mechanism which 'cranks' its input through the rules and data in the KB to arrive at a conclusion.

In ADS the rules are grouped together in *rule sets*. A rule set is made up of rules, operators, possible user input events and local working memory area. Each rule set represents the knowledge needed to perform a subtask in the flight design process. The activation of a rule set leads to the attainment of the specific goal of the subtask. The rule sets for the different subtasks form a hierarchical network of actions. The main goal is to design a flight procedure. A rule set may be activated (triggered) by a user input event or as an action of a rule that is fired in a controlling rule set.

When a rule set is triggered, the IE will exercise the rules in the rule set until no more rules in the rule set can fire. Firing of a rule normally leads to a change in the state of the working memory allowing other rules to come into play. When no more rules can be fired, control is returned to the activator of the rule set. If the rule set is triggered by a user input event, then control is returned to the MMI and the system waits for new input events. If the rule set is triggered by a higher level rule set, then control is transferred back to the originating rule set which will continue with its inference process.

The hierarchical network structure of the ADS ES is important in ensuring the efficiency of the inference process. By breaking the knowledge up into modules, localized decisions can be made efficiently and the number of rules that needs to be considered at any one time is kept relatively small. Furthermore, this layered, modular structure of the ES allows subtasks to be treated as *black boxes*. When the details for the implementation of a certain subtask change, the black box can be replaced or modified without affecting the overall organization of the system.

6.6 Pilot Implementation of the ADS Expert System

Following the paradigm outlined in the previous section, a prototype ES has been implemented in the pilot ADS. The prototype ES is relative primitive. The limitations of this prototype is summarized below.

1. The ES addresses only a subproblem of the whole Instrument Flight Procedure Design problem. Only instrument approach procedures has been considered.

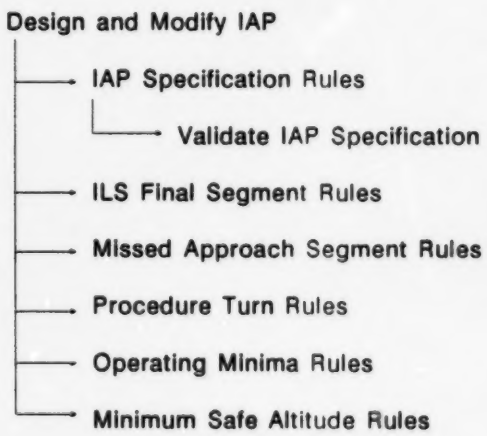
2. The ES makes extensive assumptions on the type of instrument approaches and the type of transition segments. The only types of approach segments that the prototype can design are the final segments of ILS instrument approach procedures, straight missed approach segments and procedure turns.

3. These assumptions restrict the scope of the prototype to a manageable complexity. They also allow the use of procedural operators in attaining many module goals. As a result, the network structure is simple compare to what the full-scale system would be.

4. A very simplistic IE is used. The IE is implemented as a loop that goes through the cycle of examining all the rules in a rule set and firing the applicable rules until no possible rule firing can take place in a complete cycle. In this way the IE performs forward chaining of the rules in the KB. However, there are no provision for conflict resolutions or optimization in the matching of the rules.

5. Another important deficiency of this prototype implementation is the lack of KB development tools. Only a very primitive tracing mechanism has been implemented to help in the development of the rule sets.

The prototype ES consists of the following rule sets:



The prototype implementation succeeded in providing a proof of concept. Despite its limitation, it has shown that the problem of computer aided flight procedure design can be tackled by an ES. The design process can be broken down into subtasks, each with the associated specific knowledge. Instead of imposing a rigid, predetermined sequence of events and actions, the system can be set up to use the domain knowledge in response to internal and external events.

6.7 Future Extension to the ADS Expert System

As discussed above, the prototype implementation of the ADS ES is based on incomplete domain knowledge and solves a partial problem of computer aided flight procedure design. Improvement on this prototype system can be focused in the following directions.

1. *Knowledge Engineering*. To develop the complete domain knowledge for the ES, not only must a more careful study of the existing criteria be carried out in order to extract all the relevant design expertise, but experienced flight procedure designers must be consulted to obtain the expertise not directly addressed in the documented criteria.

2. *Extension of the KB*. The rule sets in the ES must be expanded to include the rules and procedures for designing flight procedures other than ILS instrument approach procedures. This will involve a learning process in which the KB of the ADS ES will gain in scope and complexity.

3. *KB development environment*. To facilitate this learning process, a good KB development environment will be required. Tools that allow the rule sets to be created, modified and tested will ease the task of knowledge acquisition and reduce the effort required to build the full-scale system.

Development in the first two direction will make ADS into a very powerful ES tool that helps a flight procedure designer with his design task. With the third extension, ADS can be used as a criteria development tool that will enable qualified design experts to experiment with the design criteria in the continual process of criteria development.

7. OTHER ADS TOOLS AND UTILITIES

The pilot ADS provides the flight procedure designer with additional tools to facilitate the design process. These include flight procedure evaluation tools, math tools and hardcopy interface.

7.1 Flight Procedure Evaluation Tools

The Evaluate IAP menu of ADS provides the interface to two flight procedure evaluation tools.

7.1.1 Animated Flythrough

After the flight segments of an ILS instrument approach procedure have been designed, the designer can evaluate the approach procedure using an animated flythrough of the approach path with 3D perspective terrain modeling. This animated viewing provides a realistic simulation of the design domain terrain and man-made obstructions along the proposed ideal flight path. The animated viewing is implemented by means of a rapid sequence of 3D perspective displays with the viewing position placed at successive points along the flight path and the viewing direction down the path.

This flythrough simulates closely an actual on-site flight inspection, with the added advantage of not having to make any real commitments or changes. As a result, the designer can afford to explore many possible options free from cost constraints. The user can evaluate the effect of possible deviation from the ideal flight path simply by modifying the flythrough path. This evaluation tool is especially useful in situations where there are many significant man-made obstructions such as near major city centres, and where the terrain within the design domain is very mountainous.

To explore the potential of the animated flythrough evaluation tool, a second set of test data around the Pemberton area had been added. As observed during the software acceptance testing of the pilot ADS system, the animated flythrough proved to be a useful evaluation tool for the experimental MLS/STOL installation at Pemberton, B.C.

7.1.2 IAP Chart

A second evaluation tool provided by ADS is an Instrument Approach Procedure (IAP) chart display . This chart display provides a graphic summary of the ILS instrument approach procedure. The approach chart appears in its own resizable window. If ADS is configured with a hardcopy device, a printed copy of the approach chart can also be made. This chart, together with the approach procedure design summary, describe the result of an approach procedure design. A sample IAP chart is shown in Fig. 9. The design summary of this approach procedure is included in the Appendix of this report.

7.2 Math Tools

The ADS Math Tool Support supplies a Geodesic Calculator and a Desk Calculator. These tools are available to the flight procedure designer at all times during an ADS session ,and can be used for computations that might be necessary to determine a flight domain parameter specification or to verify certain results.

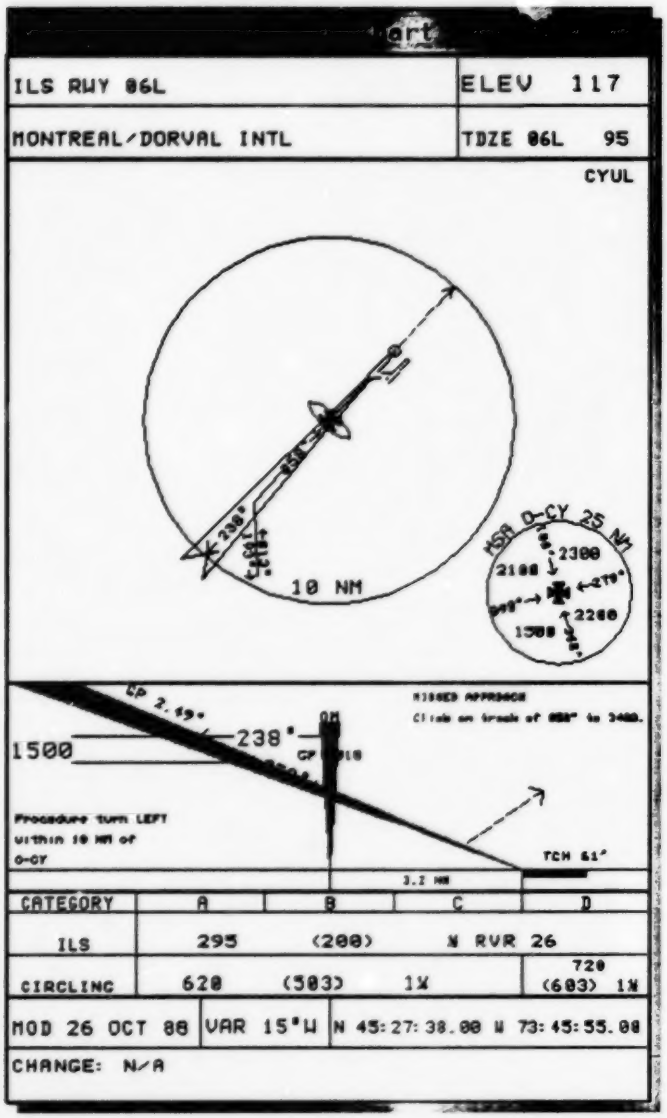


Fig. 9. IAP Chart.

7.2.1 Geodesic Calculator

The Geodesic Calculator can compute geodesic arc length, bearings and geographic positions. Such information would normally be obtained from topographical charts in the manual design process. The direct and inverse geodesics are solved using a mathematically derived earth model based on the Clark 1866 ellipsoid datum. The direct solution of the geodesic

is a function to compute the position of a geodesic point given its distance and bearing from another known geodesic point. The inverse solution of the geodesic is a function to find the distance and bearings between two known geodesic points. These functions, found in the Geodesic Calculator, are also used internally by the system for all geodesic computations.

The Geodesic Calculator also provides functions to transform between geographic latitude, longitude and a user defined Cartesian coordinate system. These transformations are useful for finding the latitude and longitude values of a point from a surface displacement value, such as the distances from the runway threshold and the runway centre line, and vice versa.

7.2.2 Desk Calculator

The Desk Calculator emulates a typical scientific desk calculator to provide 13 basic mathematical functions and 6 conversion functions. Three groups of functions are provided. The first group provides the numeric pad and the basic arithmetic operators. The second group provides the standard trigonometric and algebraic functions as well as memory register access. The third group provides unit conversion between units frequently used in the airspace design process. The layout of these functions is shown in Fig. 10.

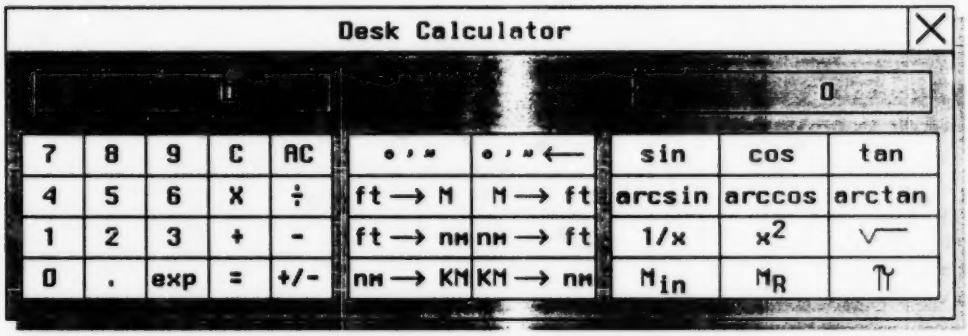


Fig. 10. Desk Calculator.

7.2.3 Magnetic Variation

All bearing computations in ADS are carried out relative to the true north. An internal function is used to compute the local magnetic variation at a point and to convert the true bearing to magnetic bearing. Magnetic variation at any point in the design domain can be obtained by centering the contour map at the point of interest and reading the magnetic variation from the "Design Domain" menu or the "Design/Modify IAP" menu.

The magnetic variation is computed using spherical harmonic expansion based on the 1980 International Geomagnetic Reference Field (IGRF 1980). Local correction using a spherical cap harmonic residual model, the Canadian Geomagnetic Reference Field 1985 (CGRF 1985) [7], is also available although not currently used in the pilot system.

7.3 Hardcopy Interface

During the development of the pilot ADS system, an interface for making hardcopy prints of screen images with an Imagen printer/plotter was developed. The hardcopy support produced printed copies of both screen images and IAP charts. This facility was useful in recording various intermediate results during the software implementation. This hardcopy interface can be adapted to provide printer access to other printing facilities in the future.

8. CONCLUSION

8.1 Project Summary

The pilot project to implement ADS using graphics workstation lasted 18 months. In the coding phase, up to four software engineers worked in parallel. Approximately 40% of the effort was expended in understanding the problem, the user requirements, and on an in-depth conceptual design of the perceived full-scale system. Throughout the project development, VPI and the Technical Committee worked very closely together. As a pilot project, it succeeded in meeting the requirement initially defined, and in setting the direction for future development.

A Silicon Graphics Iris workstation was acquired in the early stages of the project to facilitate development efforts. This workstation, installed in the Ottawa office of AIS, Transport Canada, is available for user evaluation of the pilot system.

In addition to the effort directly attributed to this pilot project, Virtual Prototypes Inc. contributed to the development by providing its unique prototyping environment and state-of-the-art man-machine interface expertise.

8.2 Results and Recommendations

The flight procedure design domain environment of the pilot ADS illustrates the power of centralizing design domain information. The complete design domain environment offered by ADS not only facilitates the task of the flight procedure designer but, by providing all the required information, can prevent unnecessary and inadvertent errors. The added dimension of visualization also provides more effective use of the information.

The MMI is the communication link between the user and ADS. It is, therefore, a crucial component of the system. A well designed MMI means that the system will be easy to learn, easy to use and, therefore, productive. The ADS MMI design emphasized the usability of the system from the flight procedure designer's point of view. Unfortunately, due to limited resources, not all the useful features identified could be implemented in the pilot system. Compromises have been made. Nevertheless, the pilot system provided a prototype that the end-users can carry out hands-on evaluations and thereby generate invaluable feedback. This feedback will influence the MMI development in the next version of ADS.

The DTED form a key component of ADS. The data are used to generate the graphic displays of the design domain. They are also used in flight domain computations. The pilot implementation verified the validity of using DTED to replace paper topographical charts. Terrain modeling based on DTED allows a completely new visual dimension to the design process by providing 3D perspective view of the design domain environment. One major difficulty in the terrain modeling was the algorithm used to tackle the hidden surface removal problem. Although it provides a near real time display model, the principal disadvantage of this algorithm is the huge amount of intermediate data generated. This posed problems in both data storage and data transfer efficiency. However, better hardware capability in the near future will make it possible to replace this with a more efficient algorithm. In the pilot system, we have only touched the threshold which opens a whole array of possibilities using 3D graphics to assist in Airspace Designs and other related areas. These possibilities remain to be developed and utilized.

The Object Data Base is another cornerstone in the ADS design domain environment. As discussed in Section 5 substantial work remained to be done in this area. This includes the refinement of the class attributes; the extension and verification of the data base; and the provision of better data base management methods.

The pilot ADS completes the first round in the development of a computer aided flight procedure design tool. As discussed in Section 6, the prototype expert system proves the viability of the expert system approach. To expand on this methodology will require more careful knowledge engineering. It is important to emphasize the need to involve human domain experts as well as written criteria in the knowledge engineering process. By analyzing the actual application of the criteria by the human experts a good set of knowledge for ADS could be extracted. Better knowledge engineering environment will also be required. By providing an interactive knowledge base development environment, ADS could be augmented from a flight procedure design tool into a flight procedure criteria development environment.

The pilot ADS has an array of useful tools and utilities to complement the major system functions. These features make the system into a total design environment. As a result of hands on user evaluations, other useful features will definitely be identified and added to this reportoire. The availability of collision risk assessment based on a mathematical model as mentioned in Section 6 will be a very useful evaluation tool to add to ADS. The integration into ADS of the existing or an improved Collision Risk Model is well worth pursuing in the future.

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ACRONYMS

ADS	Airspace Design System
AGL	Above Ground Level
AIS	Aeronautical Information Services
ARINC	Aeronautical Radio Inc.
BSP	Binary Space Partitioning
CRM	Collision Risk Model
DME	Distance Measuring Equipment
DTED	Digital Terrain Elevation Data
ES	Expert System
IAP	Instrument Approach Procedure
ICAO	International Civil Aviation Organization
IE	Inference Engine
IFR	Instrument Flight Regulations
ILS	Instrument Landing System
KB	Knowledge Base
MDA	Minimum Descend Altitude
MEA	Minimum Enroute Altitude
MLS	Microwave Landing System
MMI	Man-Machine Interface
MOCA	Minimum Obstruction Clearance Altitude
MRA	Minimum Reception Altitude
MSA	Minimum Safety Altitude
MSL	Mean Sea Level
NDB	Non-directional Beacon
OCS	Obstacle Clearance Surface

ROC	Required Obstacle Clearance
STOL	Short Takeoff and Landing
TDC	Transportation Development Centre
TDZE	Touch Down Zone Elevation
VOR	VHF Omnidirectional Range
VPI	Virtual Prototypes Inc.

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APPENDIX

An Example of an Instrument Approach Procedure Design Summary

Airport : CYUL MONTREAL/DORVAL INTL
Procedure : ILS RWY 06L
Elev : 117 ft
TDZE : 95 ft

Runway Data :
Bearing : 58 deg
Length : 11000 ft
Threshold Disp. : 0 ft
Landing Distance : 11000 ft

ILS Data :
Localizer Bearing : 58 deg
GS Angle : 2.5 deg
Localizer Position : N 45:29:07.37 W 73:44:00.68
GS Position : N 45:27:52.09 W 73:45:46.90

Intermediate Approach (Procedure Turn) :
Procedure Turn Fix : O-CY OSCAR
Inbound Course : 58 deg
Procedure Turn Type : Left
Procedure Turn Completion Dist. : 10 nmile
Procedure Turn Completion Alt. : 1500 ft
Entry Zone Governing Obstacle :

Position	ft AGL	ft MSL	ft OCA	Type
N 45:23:34.00 W 73:41:55.00	287	410	1410	Obst.

Manoeuver Zone Governing Obstacle :

Position	ft AGL	ft MSL	ft OCA	Type
N 45:18:47.00 W 73:59:00.00	0	419	1419	Cable

Final Segment :
Outer Marker : O-CY OSCAR
GS Intercept Altitude : 1005 ft
GS Altitude at Outer Marker : 1005 ft
Obstacle Clearance outside of OM/FAF :
Obstacle Clearance from OM to MAPP :
Obstacle Clearance inside of MAPP :

Missed Approach Segment (Straight Missed Approach) :
Obstacle Clearance of Initial Part :
Obstacle Clearance of Final Part :

Position	ft AGL	ft MSL	ft Clear.	Type
N 45:28:45.00 W 73:43:13.00	104	214	337	Obst.
N 45:33:30.00 W 73:37:30.00	360	503	993	Obst.
N 45:36:57.00 W 73:31:25.00	356	456	1866	Obst.

Straight-In Minima :
DH : 295 ft
HAT : 200 ft

Circling Minima :

	Position	ft OCA	ft MDA	ft HAA
CAT A :	N 45:28:45.00 W 73:43:13.00	514	620	503
CAT B :	N 45:28:45.00 W 73:43:13.00	514	620	503
CAT C :	N 45:28:45.00 W 73:43:13.00	514	620	503
CAT D :	N 45:30:50.00 W 73:45:38.00	617	720	603

Minimum Sector Altitude :

Sector	Gov. Obs. Position	ft AGL	ft MSL	ft OCA	ft MDA
N.W.	N 45:49:57.00 W 74:08:03.00	0	1017	2017	2100
S.W.	N 45:13:01.00 W 73:48:40.00	300	434	1434	1500
S.E.	N 45:30:20.00 W 73:35:32.00	45	1199	2199	2200
N.E.	N 45:33:33.00 W 73:10:06.00	0	1253	2253	2300

Date : 881031

Change Note : N/A
Deviation : N/A